

Soil heating resulting from the flaming and smoldering combustion of masticated fuels in the Rocky Mountain West

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Abstract

The objective of mastication fuel treatments is to moderate expected fire behavior by changing fuel characteristics and structure. An important consequence of this treatment is an increase in fuel loading on the forest floor. Faced with controlling wildfire or reintroducing fire in these areas, land managers are concerned about the consequences of this increased fuel loading, soil heating and the potential effects on the soil resource.

Laboratory burns were conducted to simulate summer wildfire and fall burning conditions using a range of fuel loadings and fuels from sampled masticated fuel sites in the interior Rocky Mountain region. Three experimental burn treatments were based on fuel structure at the mineral soil surface; surface fuels with the presence or absence of the duff soil horizon, and surface fuels with the presence of wet duff. The wet duff treatment was also used to evaluate two existing duff consumption models

The results of this study show that the soil heating effects of surface fuel combustion in the absence of a duff horizon results in soil heating that is dependent on surface fuel loading. Lower fuel loadings are expected to effect the below ground soil organisms and processes. Higher fuel loadings in this treatment are linked to significantly increased soil heating that is expected to alter the soil chemical properties and below ground soil communities and processes. Differences in surface fuel loading had limited effects when on duff covered soil. However, duff consumption in this treatment showed higher soil temperatures associated with physical and chemical changes within the soil.

The wet duff covered soil showed low soil heating and the unburned duff acted as an insulating layer between the burning surface fuels and the soil. The usefulness of the current duff consumption models is limited. The models incorrectly predict the estimated consumption in 60 % of the cases. The presence of significant surface fuel loading and unknown mineral content mixed with the duff are likely explanations. The results suggest that some of the soil heating effects could be moderated by burning under conditions that support lower fuel consumption and higher duff and soil moisture contents.

Introduction

Fire is a dynamic process for which the effects are both predictable and uncertain (Brown 2000). It is a common disturbance agent that has had, and continues to have, varying effects on the ecological development and maintenance of the vegetation communities and landscapes throughout the Rocky Mountain region. (Keane et al. 2002) In addition to these effects, past fire management reliance on fire exclusion and suppression has also triggered a number of significant changes at the stand and landscape scales. Attempts to reintroduce fire into these areas are limited by a number of factors including potential damage to soil and other resources due to the increased fuel loads on the forest floor. In many cases, fuel treatments such as mastication are important alternatives that can lead to eventual fire reintroduction.

Mastication is a common fuel treatment resulting in changes to fuel structure and properties which affect fire behavior. However, a common concern is that although this treatment changes the fuel bed structure, mastication does not reduce the total fuel load on a site. Land managers are concerned about the consequences of increased fuel on the forest floor and its role in soil heating because soil heating has been reported to increase the occurrence of invasive species, potentially leading to changes in stand composition and site productivity.

Soil heating results from the transfer of heat from the burning of the woody fuels and the smoldering combustion of the organic duff fuels to the soil. While heat is transferred from the combustion zone to the soil it is simultaneously transferred downward through the soil profile. The transfer of heat from the flaming combustion zone to the soil surface and then downward into the soil is influenced by soil properties including heat capacity, thermal conductivity, and diffusivity. These properties are interrelated and sensitive to temperature and the degree of soil moisture (Campbell et al. 1995). For example, the heat capacity of a soil, which is the amount of energy needed to raise the soil temperature of a unit volume of soil one degree, is higher in moist soils than dry soils due to the high latent heat of water. However, as soil temperature increases and soil moisture in the upper depths is lost or transferred during burning, the heat capacity declines, which in turn increases the rate of soil heating. Similar comparisons can be made for thermal conductivity and diffusivity, which are both moisture and temperature dependent.

Ultimately, the dependence of soil properties on moisture content has important implications on the degree of soil heating. The transfer of heat from the surface into a soil under water saturated conditions is dominated by the thermal properties of water, while the transfer of heat into a dry soil is primarily dependent on soil properties. Lin et al. (2005) reported that the moisture content of saturated soils in wetlands, with 2 cm of standing water at the surface, was sufficient to insulate soils from effects of heat due to pool burning of crude and diesel fuel.

Visual observations of the intense energy released during the flaming combustion of canopy and woody fuels suggest that extreme or severe heating of soils is common (Hartford and Frandsen 1992). In contrast with those observations, recent studies of in-situ burning of kerosene and diesel fuel have shown that the amount of energy transferred downward to the soil surface (heat flux) is a fraction of the total energy released during burning (Reardon and O'Donnell 2013, Lin et al. 2005). Other results from several studies of wildland and prescribed fire have shown that surface fire intensity is a good predictor of aboveground effects on vegetation (Duchesne and Hawkes 2000) but there is no clear relationship between surface fire intensity and soil heating (Neary et al. 2005).

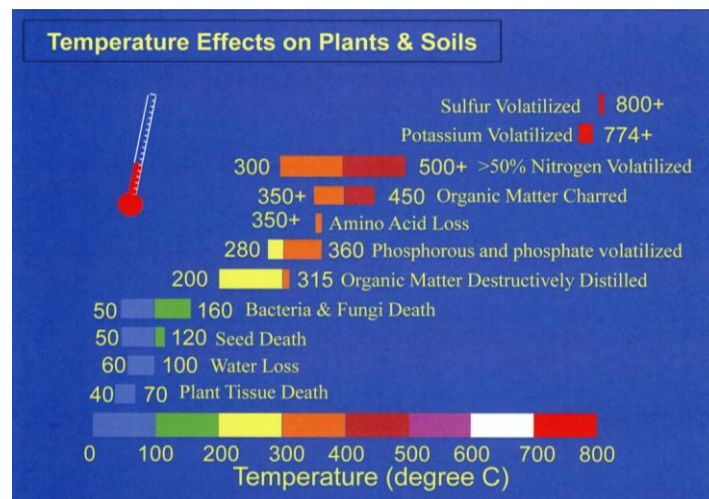
The interrelationship between vegetation communities and soil is an important factor which influences the productivity and resilience of forest and grassland communities. An example of these interactions partially explains the local distribution of forest types in Yellowstone Park. Parent material and soil are major factors that drive the distribution of the Douglas fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmanni*), subalpine fir (*Abies lasiocarpa*), and lodge pole pine (*Pinus contorta*) forest types. The former types are dominant in the Northeastern areas of the park on the more nutrient rich soils with higher water holding capacity developed from andesitic parent materials. Lodgepole pine forests are more dominant in the southern areas of the park where nutrient poor soils with lower water holding capacity developed from rhyolitic materials (Despain 1990). Similar observations have been reported for the vegetation and soils for the Big Horn in Wyoming (Despain 1973) and the Garnet Mountains in Montana (Goldin and Nimlos 1977)

In addition to contributing to nutrient and water holding capacity, soils also provide an environment in which below ground biological processes and nutrient cycling occur. Photosynthetic exudates from the roots and mycorrhizal hyphae support important processes in the rhizosphere including nitrogen fixation, nutrient turnover, and soil structure (Perry 1989). Studies have shown a significant percentage of the net primary productivity is present below ground in the roots and mycorrhizal fungi of many forest types (Vogt et al. 1982, Forgel and Hunt 1979, Korhonen et al. 2009). Elimination of the energy supplied by the exudates into the rhizosphere by fire or other disturbance disrupts these processes and may change the soil/plant relationships and result in changes in community composition, productivity and stability (Perry 1989).

Wildland fire and prescribed burn effects on plants, soils, and microbes are well documented (Neary et al 1995, Certini 2005). Fire ecologists distinguish between first order and second order fire effects to aid in understanding the multiple roles fire plays in ecosystem processes. First order effects are an immediate consequence of fire such as tree mortality, soil heating or smoke emissions. Second order effects are the result of the interactions between fire or fire-induced stress and other ecosystem processes such as the delayed downing of standing trees from wind events at a later time.

Hungerford et al (1991) presented first order fire effects of soils along a temperature gradient. The soil response can be generalized using broad temperature thresholds which reflect increasing biological and chemical sensitivity to increasing soil temperatures (Figure 1). Soil biological components such plant roots, seeds, and soil organisms are the most temperature sensitive elements in the soil. Soil temperatures greater than 60°C are commonly considered lethal to plant tissue although root mortality and desiccation has been reported at lower temperatures. Soil fungi are sensitive to temperatures in this region but lower

temperature sensitivity has been reported for the mortality of bacteria and some soil organisms. Moderately sensitive components are affected by changes in temperature between 129 °C and 300 °C. In this temperature range most soil nitrogen in the form of nitrate is lost and elements of the duff and soil horizon are destructively distilled forming hydrophobic substances and a temporary increase in soil NH_4 . At temperatures above 300 °C soil organic matter is oxidized, there is a loss of soil carbon, and the soil cations such as calcium, magnesium, sulphur and potassium are volatilized.



Laboratory burning of masticated fuel on soil monoliths was conducted to better understand the factors driving heat transfer into the soil, and the potential effects on the soil heating. Current duff consumption model were also evaluated for use under masticated fuel conditions.

Methods

Sampling

Study sites were sampled from a wide geographic area to capture the variability of factors expected to influence masticated fuel properties and loadings. Geographically, they were spread from Idaho to New Mexico in the Rocky Mountains and to South Dakota in the Great Plains

The fuel treatments on the study sites were representative of mastication methods commonly used throughout the region. Four general types of mastication equipment were utilized in this study and the range in time since mastication treatment varied from 10 to 2 years. Paired recently completed sites less

than 6 years old and older sites (6 to 10 years) were sampled at each study area, except the Black Hills, South Dakota site where only younger recently completed sites were available (Table 1).

Table 1. Sample unit location, treatment year, fuel loading and laboratory burn treatments. (BS treatment 1: surface fuels on mineral soil, DD treatment 2: surface fuels and dry duff on mineral soil, and WD treatment 3: surface fuels, wet duff on mineral soil)

Location	Site/Treatment Year	Litter kg/m²	Masticated Woody Fuels (kg/m²)	Total Fuel Load (kg/m²)	Duff Thickness cm	Burn Treatment
Boise Basin EF, ID	Amber/2004	1.29(0.17)	1.93(0.41)	3.22	2.8	BS,DD,WD
	Amber New/2010	1.24(0.25)	2.63(0.61)	3.87	2.3	BS,DD,WD
Black Hills EF, SD	BHMix/2012	1.72(0.19)	1.17(0.24)	2.89	3.1	BS,DD,WD
	BHMow/2012	1.07(0.18)	0.82(0.18)	1.89	2.2	BS,DD,WD
Manitou EF, CO	MEF Chip/2004	1.10(0.26)	2.23(0.38)	3.33	2.2	BS
	MEF WS/2005	0.73(0.15)	1.52(0.43)	2.25	0.4	BS
Deception Creek EF, ID	DC1/2004	0.48(0.08)	4.55(1.18)	5.03	2.9	BS,DD,WD
Priest River EF, ID	PR3/2011	0.60(0.11)	3.27(0.82)	3.87	5.6	BS
	PRCC1/2007	0.28(0.07)	4.29(0.99)	4.57	2.9	BS
San Juan NF, CO	Skelton/2010- 2011	1.63(0.27)	2.06(0.45)	3.69	1.5	BS
Santa Fe NF, NM	LG/2006	0.27(0.13)	3.39(0.67)	3.66	3.6	BS,DD,WD
	PAL/2011-2012	0.68(0.16)	3.55(0.80)	4.23	4.5	BS,DD,WD
Valles Caldera NP, NM	VC1/2007-2008	0.65(0.08)	4.85(0.77)	5.5	4.6	BS,DD,WD
	VC2/2012	0.97(0.21)	3.85(0.90)	4.82	2.3	BS,DD,WD

Two forest types were selected for study. Mixed mesic forest sites (n=4) located in Northern Idaho had greater than 40 cm annual average precipitation. These sites were characterized by grand fir (*Abies grandis*), western red cedar (*Thuja plicata*), and Douglas-fir (*Pseudotsuga menziesii*). Less productive conifer forest types (n=11) located in New Mexico, Colorado, Idaho and North Dakota had an average less than 40 cm annual rainfall. These sites were dominated by pure ponderosa pine (*Pinus ponderosa*) or ponderosa pine mixed with Douglas-fir (*Pseudotsuga menziesii*).

At each study site a macro plot (30 x 50 m) representative of the mastication treatment response was established. The micro plots (1 x 1 m) were sampled as part of a larger study to characterize the physical, chemical properties of masticated fuel (Keane et al. 2017)

As part of this study, surface woody fuels were collected by sub sampling (0.25 m²) each micro plot within each site macro plot. These fuels were sorted by size class and shape and mean loadings (tons/acre) were calculated on a dry mass basis by site, size, and shape class.

Undisturbed individual forest floor duff samples were collected from within each treatment unit for laboratory burning. The spatial variability of duff thickness influences the extent and severity of duff smoldering and associated soil heating. Duff thickness distribution within each macro plot was characterized using gridded sampling of the macro plot area. Measurement of duff thickness was conducted at each point on a 10 x 3 m grid within each macro plot (n=66).

Laboratory Burning

Common western wildfire and fall prescribed fire conditions were replicated during laboratory burning. The average fuel loading for each sample site and was burned on the surface of a surrogate soil monolith. Fuels were air dried fuels (RH 20 to 30 %) and the soil moisture content was less than 10%. Burning was done using litter, 1 hour, 10 hour and 100 hours fuels and the shape present on each site.

Soil heat transfer effects due to soil type differences were eliminated by using sifted quartz sand in place of native soil. The soil was contained within a ceramic box (27 cm x 18 cm x 17 cm (LWD)) constructed of 2.45 cm thick high purity refractory board which limited heat loss from the soil. Burns were conducted in a chemical fume hood with a wind speed of 1 mph at the fuel surface. A 500 watt quart lamp suspended 45 cm above the fuel surface was used to stabilize ambient temperature conditions in the hood during burning.

The soil burns were instrumented with K type thermocouples made from 28 gauge wire. Flaming combustion temperatures were captured using two thermocouples placed within the fuel. Additional temperatures were measured at 0, 2, 4, and 8 cm soil depths in the center of the burn box. The temperature

data was recorded at 3 seconds intervals during the burning and cool down of each burn using a standard laboratory data acquisition system.

Three laboratory burn treatments were designed to compare mineral soil heating that results from burning with fuel different configurations; a masticated fuel layer with no duff; a masticated fuel and duff layer; masticated fuel dry surface fuel on duff with a range of moisture contents.

In the first instance, burning fuel loads on the mineral soil surface simulated soil heating resulting from the combustion of only surface fuels. In the second instance, burning fuel loads on the dry duff surface on top of mineral soil simulated soil heating resulting from the consumption of the surface fuels and duff. The third instance, burning dry fuels on the wet duff, simulated the transfer of heat from burning surface fuel through the wet duff into mineral soil.

Soil Temperature Data Analysis

Soil surface heating differences resulting from the laboratory burning treatments were compared using a simple metric; the rate of temperature increase (above 60 °C) at the soil surface (depth 0 cm). This rate (degrees/minute) was calculated using the maximum temperature at the soil surface and the time for the soil surface to reach this maximum.

Soil temperatures and their related times at the 2, 4, 6 and 8 cm depths were placed into three broad potential effects classes which were delineated by temperature ranges between 60 °C and 120 °C, 121 °C and 300 °C and temperatures greater than 300 °C. These classes generalize potential soil heating effects along a temperature gradient; from low temperature effects on biologically sensitive organisms and processes to higher temperature effects linked to soil organic matter oxidation and the volatilization of soil cations.

As the soil heats and then cools, each depth can be characterized by multiple temperature levels over the duration of burning. However, it was assumed that the potential heating effects were dominated by the maximum temperature class at each soil depth. Soil temperatures changes during burning are reflected in measures of the duration of heating and the maximum and median temperatures. The effects of different fuel treatments were compared using the treatment level temperature and duration values from the maximum temperature class at each depth

Duff Consumption Model Evaluation

Burning treatment 3 was also used to evaluate the existing duff consumption models under masticated fuel conditions. Based on the work by Brown et al. (1985) and Frandsen (1987) the moisture content of these duff samples were conditioned to range above and below 110%. In this moisture range the

consumption of masticated surface fuels would be expected to influence the smoldering combustion of the duff soil horizon.

Frandsen (1987) reported that smoldering combustion in forest duff was constrained by moisture and duff inorganic content. The forest duff moisture content that would support smoldering combustion at a 50% probability level is expressed as a linear relationship between moisture content and inorganic content from 0 to 100%. Estimation of the probability of sustained smoldering is dependent on difference between the calculated limit and sample duff moisture content. The estimated likelihood increases with magnitude of positive differences (50 to 100%) and decreases with negative differences (50 to 0%).

$$\text{Fuel Moisture Limit}_{50} (\%) = 110 - 1.35 * \text{inorganic content}(\%) \quad \text{EQ1}$$

Brown et al (1985) developed a number of numerical models for the prediction of duff consumption for use under a range of conditions in slash and non-slash fuels from several cover types. These models integrate one or two independent variables; moisture content and preborn duff thickness. The model applied in this study (EQ2) is used for predicting percent duff reduction (DR %) from the average duff moisture content and is commonly used in the Interior West and Pacific West. In this instance, duff reduction (%) is expressed as a liner function of moisture content.

$$\text{Duff Reduction} (\%) = 83.7 - 0.426 * \text{duff moisture} (\%) \quad \text{EQ2}$$

Wet duff samples used in this portion of the analysis were conditioned to a range of moisture contents using a microwave oven. The method was adapted from Norm and Fischer (1980). Duff samples were saturated with water and then allowed to drain the loosely held gravitational water. Samples were then dried in a microwave at 50 % power for 3 minute intervals. Between drying intervals samples were removed from the microwave and allowed to equilibrate. The number of drying intervals was determined by the initial dry sample weight and the target moisture range.

Pre-burn moisture and inorganic contents of each duff sample were determined from three 5 to 10 gram subsamples from each duff sample. The subsamples were oven dried at 90°C for 48 hours and then placed in a muffle furnace at 450°C for 24 hours to determine moisture and inorganic contents respectively.

Model evaluation was conducted using estimated fuel moisture limits and percent duff reduction calculated for burn treatment 3 samples using *Eq1* and *Eq2* respectively. These estimates were compared with the observed results of laboratory burning. Post hoc analysis of burned and unburned duff samples to look at differences in model sensitivity to low and high moisture and mineral contents associated with burned and unburned samples.

Results

Soil Surface Heating

The maximum temperatures measured within the surface fuel and duff combustion zones for all treatments ranged from 318.6 °C to 708.9 °C, 314.3 °C to 565.2 °C and 345 °C to 561.1 °C respectively. Average heating durations of heating in the combustion zone were 220.4 and 462.9 and 613 minutes respectively (Table 2).

Table 2 Temperature range, average maximum temperatures and temperature range in the combustion zone (SE is the standard error of the mean value)

Treatment	Maximum Temperature Range °C	Average Maximum Temperature °C (SE)	Average Duration Minutes (SE)
#1 Surface fuel/Bare Soil	318.6 - 708.9	485.9(30.1)	220.4(25.4)
#2 Surface Fuel/Duff	314.3 - 565.2	434(21.5)	462.9(58)
#3 Surface Fuel/Wet Duff	345 - 561.1	345.6(50.8)	613(66.1)

Treatment 1 mean soil surface temperature and heating duration under surface fuels was 181 °C and 115 minutes. Higher treatment 2 mean temperatures and durations were observed on the soil surface (0 cm) under surface fuels and dry duff, 304 °C and 27 minutes respectively (Fig 2). The calculated mean rate of temperature increase at the soil surface, which combined temperature and duration, was higher for treatment 1, 10.8°C/minute than treatment 2, 3.7 °C/minute (Figure 3).

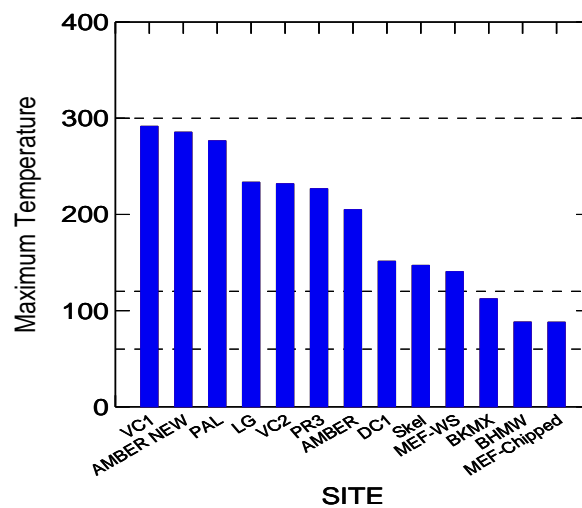


Figure 2 Treatment 1 maximum temperatures at the soil surface. Temperature limits shown at 60°C, 120°C and 300°C.

Within treatment 1, the surface temperature and duration of heating were positively correlated with masticated fuel loading ($r^2=0.80$, $p < .001$). In contrast, there was no relationship between surface temperature and loading for treatment 2 burns.

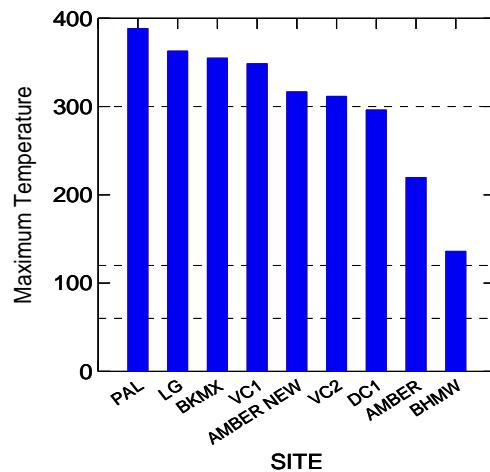


Figure 3 Treatment 2 maximum temperatures at the soil surface. Temperature limits shown at 60°C, 120°C and 300°C.

The treatment 3 samples with high duff moisture and limited consumption, (masticated fuel/wet duff) class showed no soil surface heating ($n=12$). In contrast, wet duff samples ($n=6$) that were consumed showed a surface heating range of 157.2°C to 409.7°C with an average duration of 187.6 minutes. The mean rate of temperature increase of the burned treatment 3 samples was 1.6°C/minute.

Heating effects

The results show potential heating effects from laboratory burning were influenced by burn treatment and depth. Treatment 1 burns showed the potential for effects in the low (60 to 120°C) and moderate (120 to 300°C) effect classes. The low temperature class burns had an average burn duration of 164 minutes and the average maximum temperature decreased from 77°C at 2 cm to 62°C at 8 cm. Moderate effect burns in treatment 1 had an average duration of 479 minutes and average maximum temperatures of 148°C at 2 cm and showed a decrease to low temperature effects of 65°C at 8 cm.

Temperatures in 7 of 9 treatment 2 burns showed potential effects in the moderate class. The burns had average heating duration of 622 minutes with a maximum temperature 181 °C at 2 cm which decreased to 104 °C at 6 cm. The remaining treatment 2 burns were classified as low and high temperature classes. Average maximum temperatures of the low class temperatures were 70 and 65 °C at 2 and 8 cm while temperatures of 400 and 171 °C at 2 and 104 °C at 8 cm were found for the high temperature burn.

Model Evaluation

Two duff samples from nine sites were burned in treatment 3 for duff model evaluation (n=18). Surface fuels were conditioned to low moisture contents while duff fuels were conditioned to moisture contents ranging from 58 to 201%. The average duff mineral contents of these sites ranged from 27 to 88 %. Of the 18 samples tested in this treatment, 6 samples had duff consumption rates of approximately 90 % or greater while 12 samples had consumption rates of approximately 10 % or less.

Fuel Moisture Limit₅₀ estimates, which are dependent on duff mineral content, were calculated using *Eq 1*. The estimated moisture limit of sustained smoldering averaged 20.92% and a range of 0 to 75.6 % for all treatment 3 samples. Analysis of duff moisture conducted using a post hoc classification of burned and unburned samples shows the average moisture contents of the burned and unburned duff samples was 101.7 and 144.6 % respectively. There was overlap in the burned and unburned sample moisture content ranges; 58.6 to 139.3% and 138.8 and 201.7% respectively.

Duff reduction estimates, which are dependent on duff moisture content, were calculated using *Eq 2*. Reduction estimates averaged 30 % with a range of 7 to 57 % for all treatment 3 samples. Estimates limited to samples with burned surface fuel and high duff consumption show an average of 39.5 % with a sample range of 23 to 57 %. Estimates calculated using *Eq2* for the burned samples under-estimated the observed consumption by an average of 64 %. In comparison, estimates restricted to samples with burned surface fuel and no duff consumption show an average of 25.2% with a sample range of 7 to 34 %. Estimates calculated with these samples over-estimated the observed consumption by an average of 29.8 %.

Discussion

This study shows the results of laboratory burning of masticated fuels from a number of sites across the Rocky Mountain region. The burn treatments replicated the fuel structure on the mineral soil surface; surface fuels, surface fuel and duff and surface fuel and wet duff. Burning was conducted to simulate wildfire and fall prescribed burning conditions when high rates of fuel consumption are expected due to

low fuel moisture and an increased potential of soil heating effects is expected due to low soil moisture content.

Soil heating results from the transfer of energy from the combustion zone into the soil but this energy or heat flux is not easily modeled due to the complexity of energy transfer processes at the interface between the combustion zone and soil surface (Chinanzvavana et al., 1986). The overlap of maximum temperature ranges within the flaming and smoldering duff combustion zones across sites reflect this complexity.

The overlap of combustion zone temperatures resulted from a number of factors including; the similarity in fuel chemistry properties across sites. In comparison Valette et al (1994) reported that the maximum temperatures from burning within the fuel ranged between 620°C and 670 °C over a range of fuel loadings from one site.

Maximum temperatures within the surface fuel and duff combustion zone were higher than temperatures at the soil surface. In comparison with combustion zone temperatures, the lower surface temperatures reflect the dynamic nature of soil heating which results from the simultaneous transfer of heat from the combustion zone to the soil and the transfer from the soil surface deeper into the soil profile. The range of surface temperatures soil in this study, 181 °C to 304 °C, is lower than reported in several other studies. Busse (2005) reported temperature in the 500 °C to 600 °C at the surface of dry soils under masticated wood mulch fuels while Valetta et al (1994) reported maximum temperatures of 375 °C at the soil surface in low intensity fires with low loading of needle litter and surface fuel

The placement of thermocouples at the soil surface is a potential source of measurement inconsistency and is a critical factor influencing surface temperature measurements. Errors can result if the heat transfer path between the thermocouple and the surface is poor or if the thermocouple position is uncertain (ASTM 1993). Neary et al. (1999) illustrate the significance of small position differences. That study reported large temperature differences between surface measurements and measurements at 25 mm below the soil surface. Measurement error due to thermocouple contact with the soil surface is more difficult to quantify.

Treatment 1 and treatment 2 show a difference in the evolution of temperature change over time. The rate of temperature increase at the soil surface was faster for soil with surface fuels rather than surface fuels and duff where the maximum surface temperatures also reflect the longer duration of the smoldering of duff fuels. The results show surface fuel loading is important driver of surface temperatures on bare soil but not on treatment 2 surface fuel and duff covered soil.

Maximum soil temperatures and heating duration from the laboratory burning treatments were linked to potential soil heating effects by means of three temperature classes. These classes were distributed along a

gradient of 60 °C to 300 °C and greater. These classes follow a gradient from effects dominated by changes to biological organisms and processes within the soil to changes resulting in the consumption of soil organic and the volatilization of soil nutrients. The lower bound of these classes is 60 °C which has long been considered the lower lethal temperature limit of below ground plant structures and soil organisms while the upper limit of these classes is 300 °C or greater which is considered the temperature threshold at which organic matter begins oxidation.

The estimated heating effects from the combustion of masticated surface fuels (treatment 1) changes with fuel loading and depth within the soil profile. Low temperature effects are estimated to affect the below ground biological community. Although soil temperatures did change with depth, the severity of the potential effects did not change from 2 to 8 cm depths. The soil temperatures of the moderate effects classes are expected to alter the physical and chemical soil properties. In comparison with the low temperature effects class, the severity of the effects class decreased over the 2 to 8 cm depths. The change in the potential response from low to moderate effects within treatment 1 is linked with fuel loading. The sites with the higher woody fuel loads showed soil surface temperatures and temperatures at 2 cm and greater soil depths than sites with lower masticated surface fuel loadings.

The soil heating response to the combustion of surface fuels and the smoldering of the duff fuels (treatment 2) was dominated by effects in moderate temperature class at the 2 and 4 cm depths and effects in the low temperature class at the 6 cm depth. Treatment 2 burns are estimated to affect soil chemical and physical properties closer to the soil surface and have an effect on biological organisms and properties lower in the soil profile. However the maximum temperatures and durations of treatment 2 moderate effects burns were higher than the temperatures and durations of treatment 1 burns with moderate potential effects

Treatment 2 burns showed no relationship between surface fuel loading and soil temperatures at 2 cm and greater depths. In contrast with treatment 1 burns, the temperatures within the soil profile of the treatment 2 burns are related to duff thickness. Sites with the thicker duff fuels produced potential high temperature effects while sites with low duff fuels resulted in lower temperatures and potential effects in the lower temperature range.

There were no potential soil heating effects for burns in treatment 3 that did not sustain combustion of the duff fuel. However, low and moderate effects were estimated for the wet duff burns (treatment 3) with greater than 90 % duff consumption.

Models of duff consumption or reduction play an integral role in the development of prescribed burning prescriptions and the evaluation of potential fire effects in soil. Two commonly used models for estimating duff consumption were evaluated for use with masticated fuels. These models presented an opportunity to assess the influence of masticated fuel, duff moisture and mineral content on duff consumption. Many duff characteristics such as bulk density and mineral content vary both across and within sites. Several studies have reported the influence of these properties on smoldering combustion processes (Peter, 1992, Frandsen 1987, Hartford 1993). Owing to its high latent heat of vaporization the moisture in duff represents a significant heat sink during smoldering combustion (Peter 1992, Frandsen 1987). However, given that mineral content is correlated with bulk density in organic soils; gravimetric moisture content comparisons of duff samples with unlike mineral contents are misleading because they misrepresent the absolute amount of water in the samples (Boelter 1964).

Mineral soil is often incorporated in the duff soil horizon as a result of biological and physical processes including forest management activities (Hartford 1993). EQ1 expressed an inverse linear relationship between duff mineral content and the moisture content limit supporting smoldering. This moisture limit decreases with increasing mineral content and the likelihood of smoldering increases below this limit and decreases above this limit. The degree of this increase or decrease is a function of the difference between the predicted moisture limit and the estimated sample moisture (Frandsen 1987).

The application of Eq2 to the wet duff samples shows a low fuel moisture limit of 29% which was primarily a result of the high duff mineral content associated with masticated sample sites. In comparison, Frandsen (1987) reports a moisture limit of 110% for duff or peat with a mineral content of 0 %. In this case, this moisture limit predicts that moistures below 29% would support smoldering while increases in moisture above this limit would decrease the smoldering potential. The results shown the average moisture content of the burned samples was 101.4%. Based on model predictions the probability of sustaining smoldering combustion is low because the moisture content is substantially above the estimated limit of 29%.

The second model EQ2 is dependent of duff moisture and duff reduction (%) is expressed as an inverse linear relationship between duff moisture and reduction (Brown et al, 198?). In this case, the results show that the sensitivity of model EQ2 is dependent on moisture content. This model predicts a max consumption rate of 84% at 0% moisture content and no consumption above 196%

The results show consumption was greater than 90% at an average moisture content of 101.4 % while no consumption was observed above an average moisture content of 139%. Comparison of these post burn observations with model predictions with show this model underestimates duff reduction at lower moisture contents while over estimating reduction at the higher moistures.

The results show the limitations of both models. The observations from the laboratory burns are not consistent with the model predictions of either the likelihood of smoldering combustion or duff reduction. But the post burn observations are consistent with burning guideless that suggest the burn/ no burn moisture content threshold is between 101% and 139%. Some of the difference can be attributed to the burning of the surface fuel. Research has suggested that burning of 0 to 3 inch fuel on the forest floor influences duff reduction (Norum 1977) while surface loading of less than 2.5 tons an acre would have little effect on reduction (Brown et al 1985). However it appears unlikely that surface fuel loading alone would explain the inconsistency between the predicted and observed duff response. Additional work needs to be conducted to address duff heating and drying of duff fuels due to surface fuel loading and the influence of variation in duff characteristics such as bulk density and mineral content due to mastication treatments

Laboratory burning improved our understanding of the relationship between masticated fuel loadings and soil heating. The maximum soil surface temperatures of treatment 1 burns were highly correlated with surface fuel loads in the absence of a duff horizon. As a consequence of dry fuel and dry soil burning conditions, low surface fuel loadings were estimated to affect the below ground biological community from 2 to 8 cm depths while higher surface fuel loadings were estimated to effect soil physical and chemical properties in the upper soil profile accompanied by lower temperature effects at 6 to 8 cm depths within the soil profile. In comparison, surface fuel loads of the treatment 2 burns incorporated a dry duff fuel layer within the fuel structure. The surface fuels of this burn treatment were not correlated with the maximum soil surface temperature response .Maximum surface temperatures were higher than treatment 1 temperatures and the effects at 2 cm and 4 cm depths included more severe changes to the physical and chemical soil properties and lower temperature related changes to below ground biological communities and properties at depths of 6 to 8 cm.

The effects of incorporating a wet duff fuel layer within the fuel structure were dependent on the duff moisture content. The mean soil surface temperatures were unaffected by burning surface fuels under duff fuels with moisture contents too high to sustain smoldering, However, when the duff fuels did sustain smoldering the soil surface temperature response was similar to treatment 2 burns. The results suggest that some of the soil heating effects could be moderated by burning under conditions that support lower fuel consumption and higher duff and soil moisture contents.

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